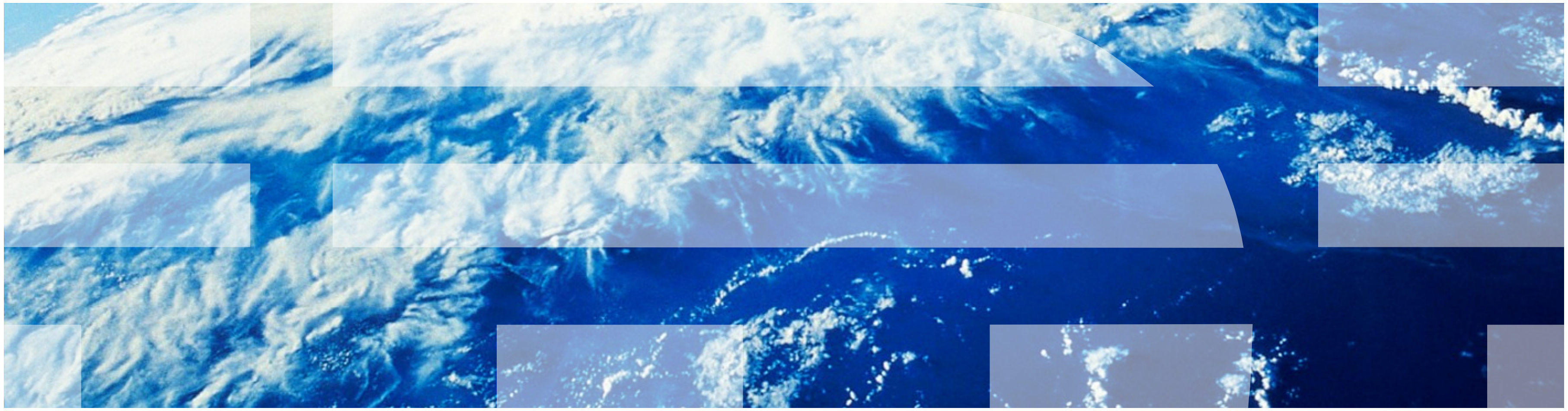
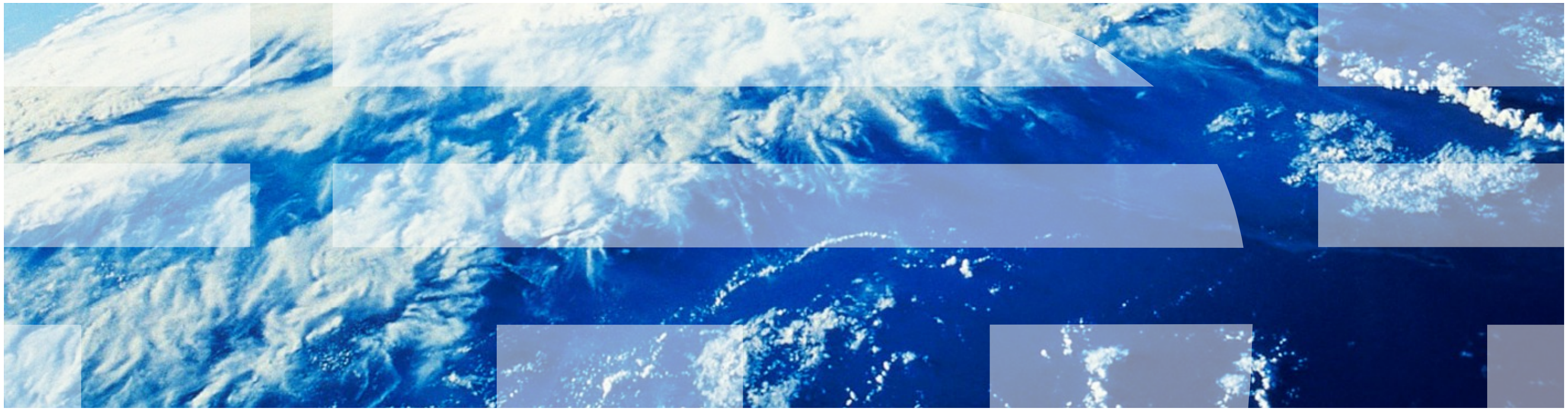
Lecture 1



Computer Systems for Data Science
Topic 1

Course Introduction

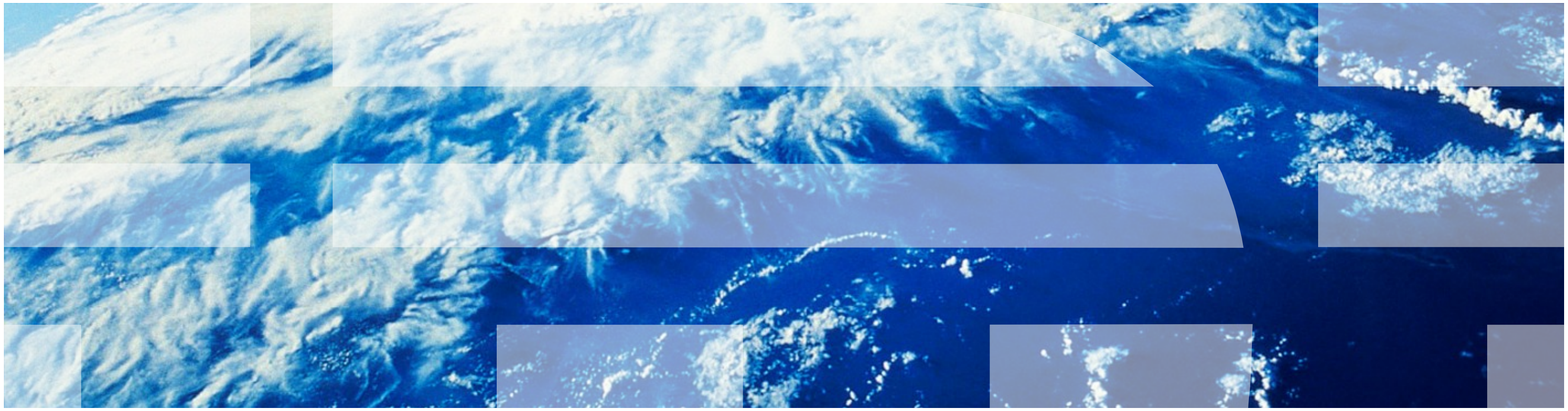
Systems concepts



Agenda

- Intro to instructors
- High-level overview
  - What is data science and big data?
  - Class goals and why should you care?
- Class logistics
  - How the class is going to work?
- Performance and systems rules of thumb
- Intro to datacenters

Who Are We?

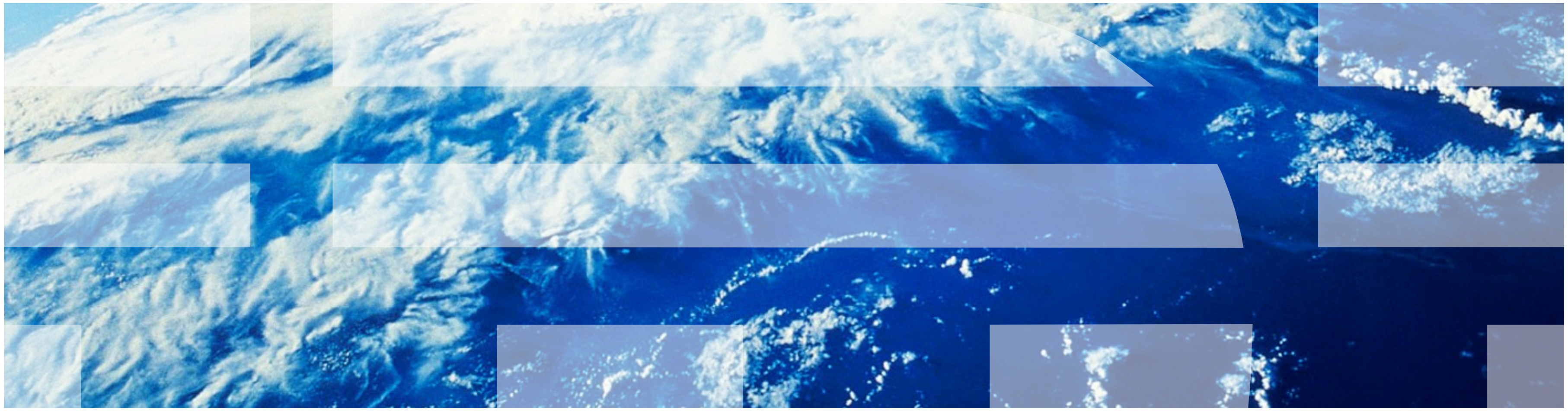


Course Instructors and TAs

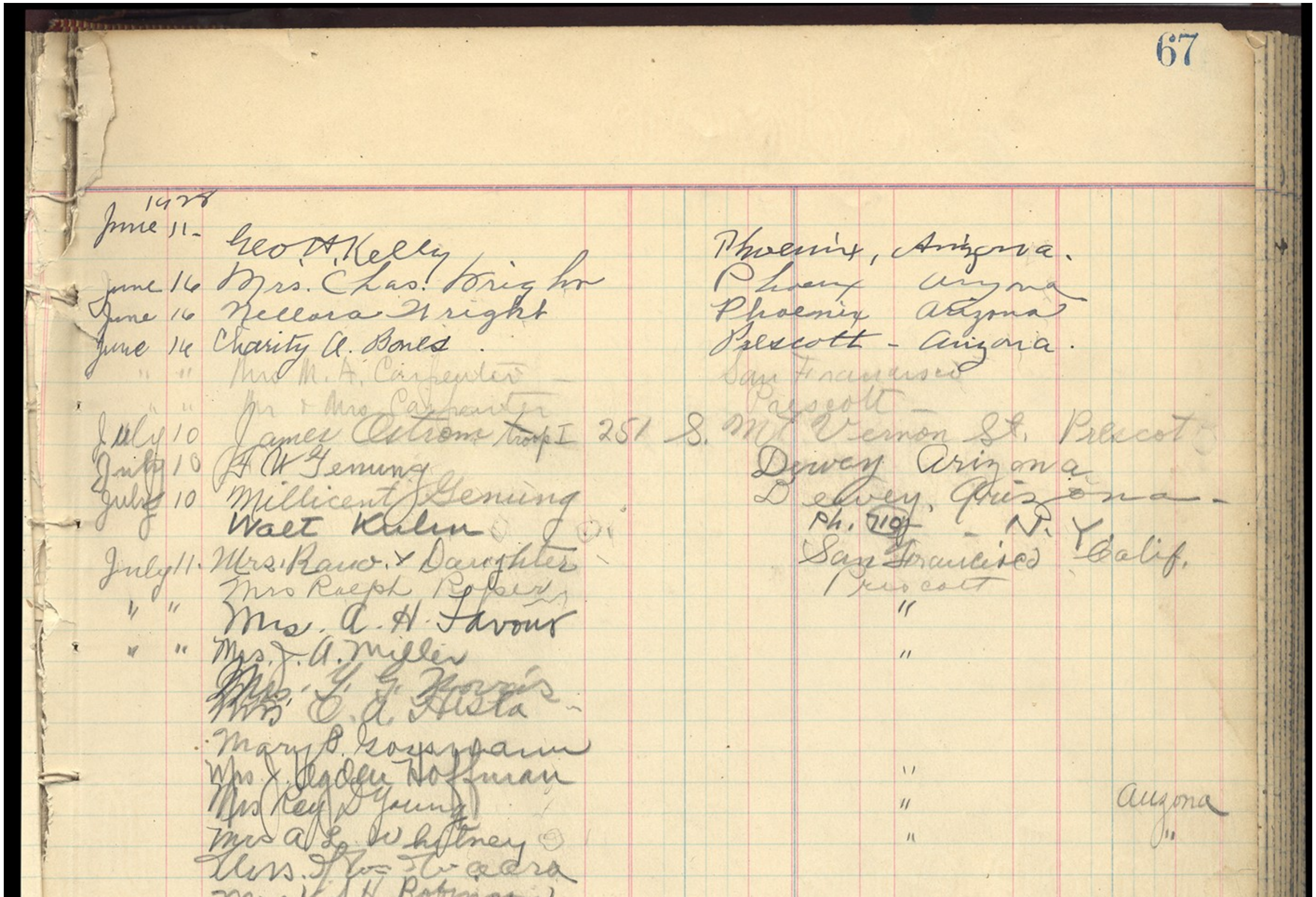
- Instructor: Asaf Cidon
  - New Columbia EE + CS professor
  - Research focus: infrastructure for big data, storage systems for big data
  - Before Columbia, founded Sookasa, cloud storage security company (acquired by Barracuda Networks)
  - Built big data systems and used them both in academia and in industry
  - Type of problems I've worked on:
    - Automatic classification of spear phishing
    - Anomaly detection of users within organization
    - Sensitive data exfiltration…

- Head TA: Hongyi Wang
- TAs: Yu Jian Wu, Ke Li, Mingen Pan, Qianrui Zhang
- All Tas have experience in databases and systems
  - Hongyi and Yu Jian helped create course homework

What is Data Science and Big Data?



This was a system for big data



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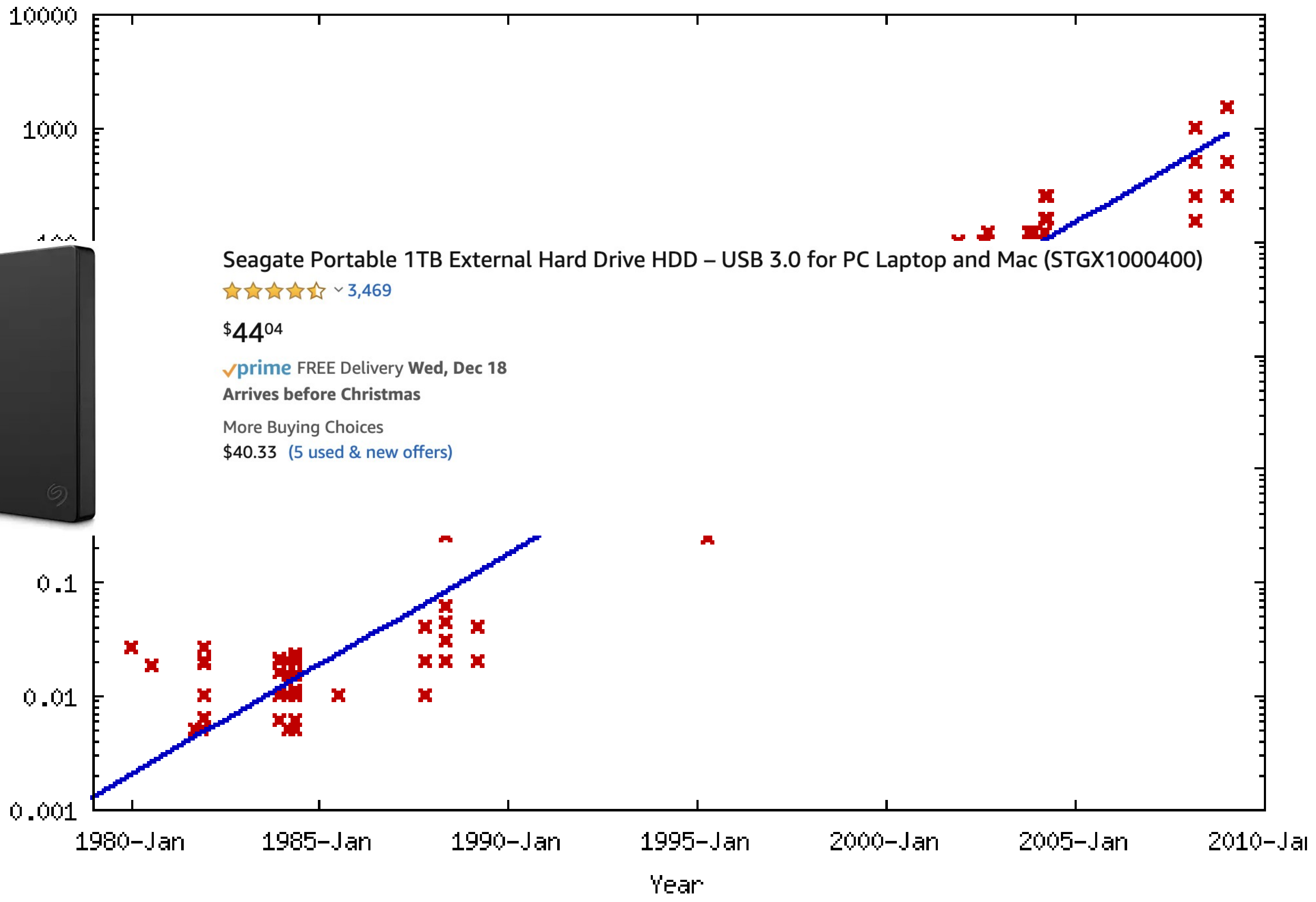
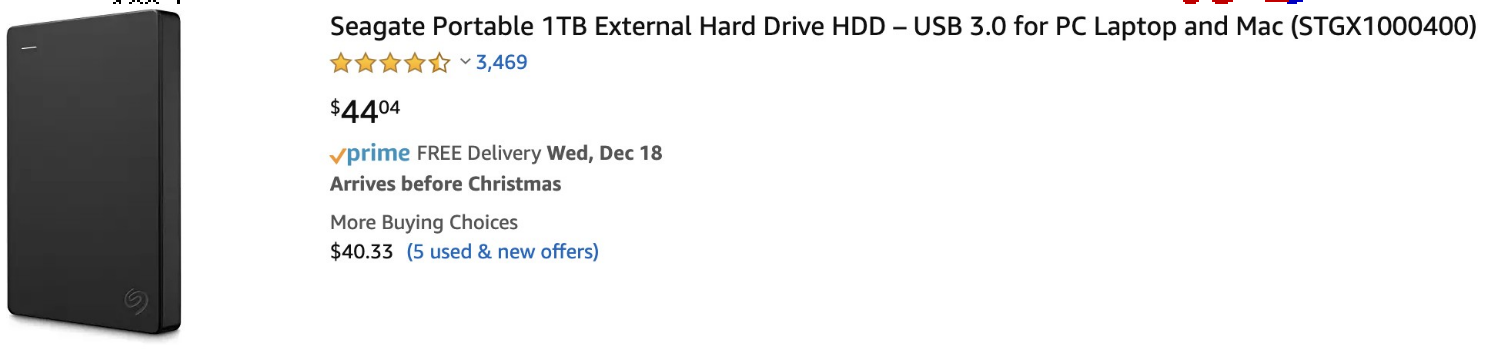
1928 June	11	Geo. A. Kelly	Phoenix, Arizona.	
June	16	Mrs. Chas. Wright	Phoenix Arizona	
June	16	Nellora Wright	Phoenix Arizona	
June	14	Charity A. Bones	Prescott - Arizona.	
"	"	Mrs M. A. Carpenter	San Francisco	
"	"	Mr & Mrs Carpenter	Prescott	
July	10	James Ostrom troop I	251 S. Mt Vernon St. Prescot	
July	10	A. W. Genung	Dewey Arizona	
July	10	Millicent J. Genung	Dewey, Arizona	
		Walt Kuhn	Ph. 710 - N. Y.	
July	11	Mrs. Rand & Daughter	San Francisco Calif.	
		Mrs Ralph Rogers	Prescott	
"	"	Mrs. A. H. Favour	"	
"	"	Mrs. J. A. Miller	"	
		Mrs. Y. G. Harris		
		Mrs. E. A. Hesla		
		Mary B. Gossmann		
		Mrs J. Ogden Hoffman	"	
		Mrs Roy D Young	"	Arizona
		Mrs A. L. Whitney	"	"
		Mrs. [illegible]		
		[illegible]		

Data science systems were expensive

Today: data is cheap




Seagate Portable 1TB External Hard Drive HDD – USB 3.0 for PC Laptop and Mac (STGX1000400)

3,469

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prime FREE Delivery **Wed, Dec 18**

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$40.33 (5 used & new offers)

Where is data coming from?

- Physical devices

Where is data coming from?

- Physical devices
- Software logs

Where is data coming from?

- Physical devices
- Software logs
- Phones

Where is data coming from?

- Physical devices
- Software logs
- Phones
- GPS/Cars

Where is data coming from?

- Physical devices
- Software logs
- Phones
- GPS/Cars
- Internet of *Things*

Examples of data science

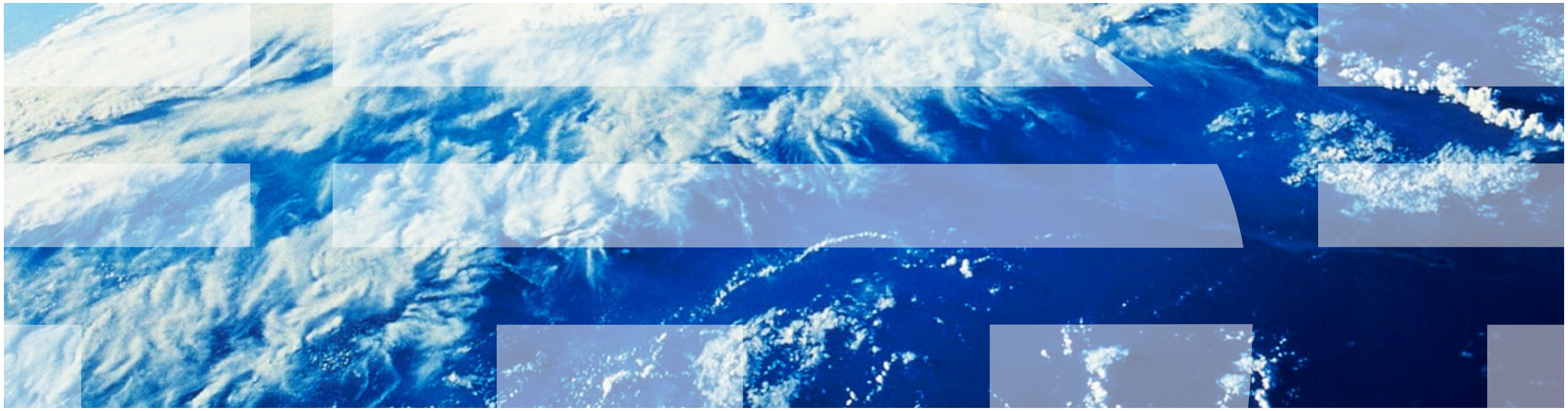
- What video should I recommend to this user to view next?
- Does this MRI image of a breast contain a tumor?
- Who is going to win the election?
- Which cities in the US will have high incidence of flu in 2 weeks?
- Is the object across from the car a pedestrian?

What is big data?

- “**Extremely large data sets** that may be analyzed computationally to reveal patterns, trends, and associations, especially relating to human behavior and interactions” – Oxford Dictionary

- What’s an extremely large data set?
  - Fits on a single machine?
  - Fits on 10 machines?

Class Goals



Our focus in this class: **Computer Systems** for Data Science

- Questions we **will** answer in this class:
  - How are big data systems designed?
  - How to store the data?
  - How to query/analyze the data?
  - How do we ensure uptime/availability to the data?
  - How to ensure privacy/security/quality?
- Questions we **won't** answer in this class:
  - What algorithm should we use?
  - How to use ML for big data?
  - How do we explain/debug ML models?
  - How can data be visualized?
  - What are the statistical/mathematical foundations for data science?

Course Objectives

- **Graduate level course**
- **Broad overview of cloud systems that are used in data science**
  - **Database** related topics (DBMS, SQL, NoSQL)
  - **Computer systems** foundations (throughput vs. latency, scalability vs. performance)
  - **Distributed systems** for data scientists (sharding, fault tolerance)
- Throughout the class we will focus on how **commonly used and modern** cloud-based big data systems work (Spark, Tensorflow, Hadoop file system,…)
- The class will give a **broad and hopefully practical** introduction to these topics geared towards data scientists, but **does not replace** core CS/EE classes like OS, databases, distributed systems, security, architecture
- **You come from diverse backgrounds:** Some of the content will be repetitive for students who have taken the classes above
- **Required background**
  - Programming experience with Python or equivalent
  - Programming assignments 2-3 will be in pairs in Python, so we will make sure that all pairs have at least one student who knows Python

Course Administration and Grading

- **All materials, assignments, etc. posted on course website**
  - https://cs-w4121.github.io/
- **Announcement will be posted on Piazza, courseworks**
- **Lecture Materials**
  - Lecture slides
  - No textbook (new, fast moving field)
- **Homework, assignments, exams**
  - Programming assignment 1: BigQuery (20%), alone
  - Written assignment: systems and databases (10%), alone
  - Midterm (15%)
  - Programming assignment 2: Spark (20%), in pairs
  - Programming assignment 3: Tensorflow (10%), in pairs
  - Final exam (25%)

Programming Assignments

- 3 programming assignments
  - Assignment 1 is solo, assignments 2-3 are in pairs
- Programming assignments 2-3 are in Python
  - If you don't know Python
    - Pair with someone who does
    - A useful language to learn!
- All assignments in Google Cloud (GCP)
  - Goal: familiarize yourself with working in public cloud environment
    - AWS / Azure / GCP are similar
    - Many systems and deployment details are hidden / automated (but we won't ignore them!)
    - We will be focusing on systems-level problems, not on algorithms
  - We will provide GCP credits, if you run out contact us
    - If you reach $10 of credits or less, please contact Mingen: pan.mingen@columbia.edu
    - But be careful not to spend too many!
- Programming assignment goals
  - Assignment 1: BigQuery
    - Learning to use SQL on a big data set
  - Assignment 2: DataProc + Spark + HDFS + Streaming
    - Understanding Spark, Streaming systems concepts
  - Assignment 3: Tensorflow
    - Understanding Tensorflow and basic ML training systems problems

Tentative Contents and Syllabus

- Computer systems and performance rules of thumb
  - Latency vs. throughput
  - Amdahl's law
  - Back-of-the-envelope systems math
  - Performance bottlenecks
- Data centers
  - What is a data center?
  - Data center failures
  - Achieving reliability with smart software
- Databases
  - Relational model and SQL
  - SELECT, FROM, WHERE
  - GROUPBY
  - JOINs
  - Nested queries
  - Transactions
  - ACID
  - OLAP vs. OLTP, SQL vs. NoSQL
  - Indexing
  - Logging
  - **System highlight: BigQuery, MySQL**
- Storage and distributed file systems
  - Storage technologies primer
  - Distributed file systems
  - **System highlight: Hadoop File System (HDFS), amazon S3/Google Cloud Storage**

Tentative Contents and Syllabus

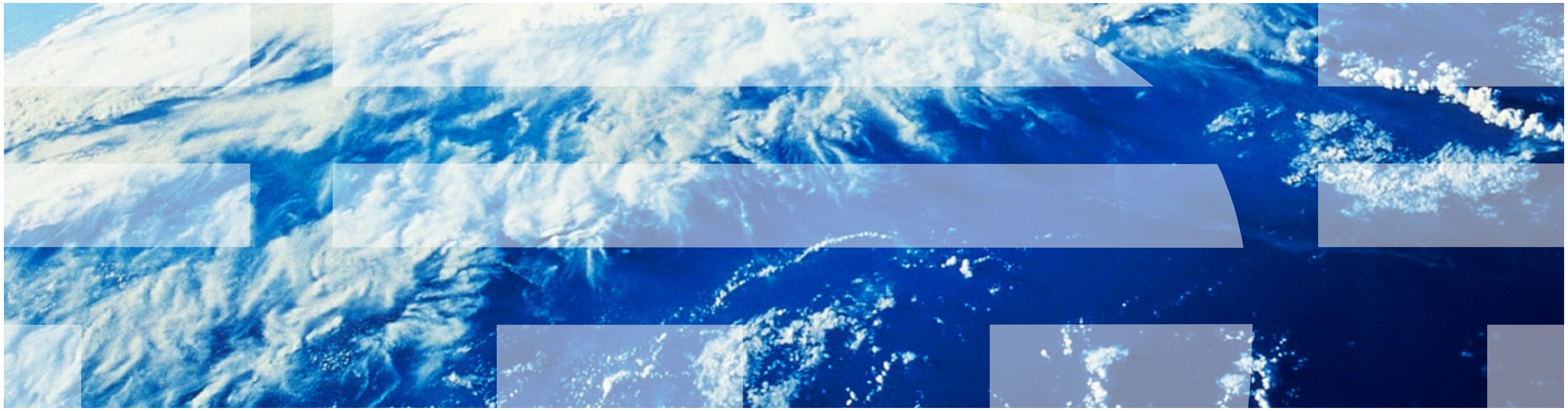
- Distributed systems
  - 2 Phase Commit
  - Locking
  - Sharding
  - Fault tolerance
  - Replication and consensus
- Mapreduce
  - Mapreduce computing model
  - Stragglers
  - Importance of 99th latency
  - Strategies to mitigate tail latency and increase availability
- Distributed analytics and streaming
  - Resilient Distributed Dataframes (RDD)
  - Fault tolerance in distributed analytics: lineage
  - Streaming computing model
  - **Systems highlight: Spark, Google Dataproc, Spark streaming**
- Caching
  - Performance benefits
  - When to use a cache? (hint: almost everywhere □)
  - Consistency and performance considerations
  - Eviction policies
  - **Systems highlight: Memcached and Redis**

Tentative Contents and Syllabus

- Tensorflow and pipelines
  - Tensorflow programming model
  - ML hardware trends
  - ML pipelines
  - Data validation and data quality
  - **Systems highlight: Tensorflow and Tensorflow Extended**
- Security and privacy
  - Security of big data systems
  - Privacy consideration
  - Data compliance and access control

Adapted from David Patterson and Kathryn McKinley

Performance Concepts and Rules of Thumb



Performance Evaluation

- Metric: something we measure
- Goal: evaluate how good/bad our computer system is performing
- Examples:
  - Power consumed by our database
  - Cost of running our web application
  - Average time it takes to render a user page
  - How many users can we support at the same time
- Metrics allow us to compare two computer systems

Tradeoff: latency vs. throughput

- Pizza delivery example
  - Do you want your pizza hot?
  - Do you want your pizza to be cheap?
- Why do these conflict?
- Two different strategies for pizza company
  - Often we have a requirement for both (I want my pizza to be delivered in X time as cheaply as possible)

- Latency = execution time for a single task
- Throughput = number of tasks per unit time

- A more relevant example:
  - Assuming cars drive at 65mph, so self driving car needs to recognize an object in 0.1 seconds
  - Object recognition system needs to process 1 million object recognition tasks every second

Latency vs. Throughput is often a trade off

Plane	DC to Paris	Speed	Passengers	Throughput (pmph)
Boeing 747	6.5 hours	610 mph	470	286,700
Concorde	3 hours	1350 mph	132	178,200

- Which plane has higher performance?

- Time to do the task (execution time)
  - **Latency**, execution time, response time
- Tasks per day, hour, week, sec (performance)
  - **Throughput**, bandwidth, operations per second

Definitions

- Performance is in units of things-per-second
  - Bigger is better

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  - Bigger is better

- Response time of a system Y running Z

- Response time of a system Y running Z

  - $\text{performance}(Y) = \dfrac{1}{\mathit{execution\ time}\ (Z\ on\ Y)}$

- Throughput of system Y running many requests

- Throughput of system Y running many requests

  - $\text{performance}(Y) = \dfrac{\mathit{number\ of\ requests}}{\mathit{unit\ time}}$

- “System X is n times faster than Y” means:

- “System X is n times faster than Y” means:

  - $n = \dfrac{performance(X)}{performance(Y)}$

How do we improve performance?

- Suppose we have a database that processes two types of queries:
  - Query A finishes in 100 seconds
  - Query B finishes in 2 seconds
- We want better performance
  - Which query should we improve?
- The answer: it depends!

Speedup

- Make a change to the system
- Measure how much faster/slower it is

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- Measure how much faster/slower it is

- $Speedup = \frac{Execution\ time\ before\ change}{Execution\ time\ after\ change}$

Speedup when we know details about the change

- Performance improvement depends on:
  - How good is the enhancement? (factor S)
  - How often is it used? (factor p)
- Speedup due to enhancement E:
  - $Speedup(E) = \frac{Execution\ time\ without\ E}{Execution\ time\ with\ E} = \frac{Performance\ with\ E}{Performance\ without\ E}$
  - $ExTime_{new} = ExTime_{old} * \left[(1-p) + \frac{p}{S}\right]$
  - $Speedup(E) = \frac{ExTime_{old}}{ExTime_{new}} = \frac{1}{(1-p)+\frac{p}{S}}$

Amdahl’s law: example

- We built a new database that speeds up aggregate queries by 2x! **Hurray!**
- But.... only 10% of queries are aggregate queries
- $ExTime_{new} = ExTime_{old} * \left[(1-p) + \frac{p}{s}\right]$
- $ExTime_{new} = E$

Amdahl’s law in simple terms:
Make the common case fast!

- $Speedup_{total} =$ 0.95
- Amdahl’s law: speedup bounded by

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- Even if aggregated queries could be completed in zero time, our **maximum** speedup would be:
- $\frac{1}{fraction\ of\ time\ not\ enhanced}$

- Even if aggregated queries could be completed in zero time, our **maximum** speedup would be:

- $Speedup_{optimal} = \frac{1}{0.9} = 1.111$

Useful back-of-the-envelope latency numbers (all rough estimates)

- Time measurements:
  - Nanosecond (ns): 1/1,000,000,000 second
  - Microsecond (us): 1/1,000,000 second
  - Millisecond (ms): 1/1000 second

- CPU cache access: 1ns
- Memory access: 100ns
- Read a small random object from a local flash drive: 50,000ns, 50us
- Read a small object within the same region in a data center: 100,000ns, 100us
- Run a SQL query on a flash database: 1,000,000ns, 1ms
- Read a small random object from magnetic disk: 10,000,000ns, 10ms
- Run a SQL query on a disk database: 20,000,000ns, 20ms
- Roundtrip time over the internet: 100,000,000ns, 100ms
- Bounded by the speed of light!

Database example

- Scenario:
  - A user application running in the cloud needs to read a small object
  - It first checks if the object is already saved locally, either in the CPU cache or in memory:
    - 10% chance it’s in the CPU cache
    - If not, 20% chance it’s in memory
  - If not saved locally, it fetches it from a database from within the center network

- Compute average latency:
  - 0.1 * cache latency + 0.9 * (0.2 * memory latency + 0.8 * (remote database latency))

    = 0.1ns + 18ns + 0.72 * not in memory latency
- Remote database latency = network latency + database latency = 1,100,000ns
- Total average latency = 792,018ns or 790us
- Total average latency ~= 0.72 * not in memory latency = 792,000ns
-
- **Amdahl’s law: focus on the most common path taken**

Disk vs. Flash, Cost vs. Performance

- Acme runs a flu prediction service
- They have an app that displays a graph on the geographic spread of the flu, which requires running a SQL query on their database stored in the cloud
- Acme is considering running their database on flash vs. magnetic disk
  - Flash is 2X more expensive, but 20X faster
- An Acme user study shows that users don't notice page loading times, as long as they are under 300,000,000ns (300ms)
- Reminder: Internet roundtrip (100ms), disk DB access (10ms), flash DB acccess (1ms), read within datacenter (100us)
- Scenario 1: To compute the graph, we only need a single database access in the cloud
  - Latency with flash database: 101ms
  - **Latency with disk database: 110ms**
- Scenario 2: The app requires getting an initial response from the database, then a user input, and then another database request
  - Latency with flash database: 202ms
  - **Latency with disk database: 220ms**
- Scenario 3: The app requires 20 sequential databases accesses within the cloud to compute the graph, and then it can return
  - **Latency with flash database: 120ms**
  - Latency with disk database: 300ms

Identifying performance bottlenecks

- My application is seeing an average latency of 200ms, where is the bottleneck?
- A few guiding questions:
    1. What systems does the web page need to access? Which networks does it need to traverse?
    2. Start from the most common case + highest latency
- Example:
    - Application needs to go through the Internet ~ 1 * 100ms
    - Hits a server that first checks if the request is saved on memory cache in the cloud ~ 0.2 * 100us
    - If not (80% of the time), goes over the network and accesses a single disk database ~ 0.8 * 10ms
- Guess 1: Internet slowdown
- Guess 2: database slowdown